Effect of time on biomechanical measures during exercise on the Functional Re-adaptive Exercise Device

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Abstract

Mechanistic studies of the Functional Re-adaptive Exercise Device (FRED) have shown it automatically recruits Lumbar Multifidus (LM) and Transversus Abdominis (TrA) – two deep-spinal muscles that are atrophied and show altered motor control in low back pain (LBP). No studies have investigated the time required to familiarise to FRED exercise, which is required to inform future FRED based clinical trial protocols. This study therefore determined the effect of time, during FRED exercise, on biomechanical outcome measures, to establish the familiarisation period, and assess for loss of technique throughout a ten minute trial. A cohort comparison study of 148 participants, 70 experiencing low back pain, had lumbopelvic kinematics, exercise frequency and movement variability measured during a 10 minute trial. Magnitude-based inference was used to assess for familiarisation, using plots of variation over time with familiarised reference ranges. The no pain group took 170 seconds, and the back pain group took 150 seconds, to familiarise. A familiarisation period of at least 170 seconds (2.8 minutes) is recommended. This justifies, and provides a familiarisation time for use of the FRED as a motor control intervention.

Keywords: Motor control, spinal rehabilitation, Lumbar Multifidus, Transversus Abdominis

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Introduction

Low back pain (LBP) costs over £1billion per year (NICE, 2009) in addition to psychosocial challenges, creating a need for low cost and effective treatments. While LBP is multifactorial(Panjabi, 2006), spinal robustness at an inter-segmental level (Panjabi, 1992a, 1992b) and changes in spinal mechanics (Panjabi, 2006) are commonly reported elements. An adequate level of spinal robustness is required to ensure static and dynamic stability of the spine with robustness referring to both stability and how the spine, muscles and motor control system cope with disturbances such as a perturbation (Reeves, Narendra, & Cholewicki, 2008). The Lumbar Multifidus muscle (LM) provides segmental stiffness (Kiefer, Shirazi-Adl, & Parnianpur, 1998; Panjabi, 1992a) and controls lumbar lordosis(Claus, Hides, Moseley, & Hodges, 2009) while the Transversus Abdominis muscle (TrA) provides segmental robustness by increasing intra-abdominal pressure (J. Hides, Stanton, Mendis, & Sexton, 2011b; Hodges, 2004). Dysfunction and atrophy of both muscles has been linked with a lack of spinal robustness and therefore LBP (J. Hides, Lambrecht, Stanton, & Damann, 2015; J. Hides, et al., 2011b; Hodges and Moseley, 2003; Saunders, Coppieters, & Hodges, 2004; Wallwork, Stanton, Freke, & Hides, 2009). It is often difficult for individuals to voluntarily recruit these muscles, especially LM(Van, Hides, & Richardson, 2006), which is a challenge for rehabilitation.

Recently, the Functional Re-adaptive Exercise Device (FRED), that aims to target recruitment of the LM and TrA muscles, has undergone mechanistic investigations to assess its potential as an intervention for LBP and determine future clinical trial protocol parameters (Caplan, Gibbon, Hibbs, & Debuse, 2014; Debuse, Birch, Gibson, & Caplan, 2013; Gibbon, Debuse, & Caplan, 2013). Exercise on the

FRED involves a combination of weight-bearing, an unstable base of support (at the feet) and an upright posture with a robust lumbo-pelvic region during functional lower-limb cyclical motion at a slow target speed. The FRED is similar to an elliptical trainer but with no resistance and a requirement to perform the movement with minimal variability in movement speed. A more detailed description of the movement on FRED and determination of target exercise speed, with images, is available elsewhere (2017c). Recent studies of FRED exercise shows it automatically recruits both LM and TrA (Debuse, et al., 2013; Winnard, et al., 2017c) through a tonic contraction (Caplan, et al., 2014) with no conscious input, as well increasing spinal robustness (Gibbon, et al., 2013) and placing the spine into a more optimal position for LM and TrA activity compared to walking, which is a similar upright functional exercise (Winnard, D., Wilkinson, Tahmosybayat, & N., 2017b) . These studies have justified clinical trials of FRED as an intervention for LBP.

To date, FRED studies have included exercise familiarisation periods of two to three minutes (Debuse, et al., 2013), or five minutes (Caplan, et al., 2014; Gibbon, et al., 2013; Winnard, D., et al., 2017b; Winnard, et al., 2017c). These familiarisation periods, however, have not been determined objectively. As a final stage of the mechanistic studies, before a clinical trial, it was necessary to determine the time required to familiarise to FRED exercise in terms of pelvic and spinal kinematics, exercise frequency and movement variability. The same familiarisation time could also be used clinically, should the device prove useful from clinical trials, without clinicians having to rely on arbitrary or trial and error derived familiarisation periods. The aim of this study was therefore determined the effect of time, during

FRED exercise, on biomechanical outcome measures, to establish the familiarisation period, and assess for loss of technique throughout a ten minute trial.

Methods

The study protocol was approved by the Northumbria University ethics committee. Participants provided written informed consent before participating. One hundred and forty eight participants were recruited from the general public, with a mean (±SD) age, height and mass of 36.7 (±9.0) years, 1.72 (±0.09) m, and 77.8 (±17.5) kg, respectively. The study was conducted fully open to the general public at a local science museum in Newcastle-Upon-Tyne as part of a "Meet the Scientist" interactive exhibit and the general public visiting the museum over a four week period were able to choose to take part in the study. Exclusion criteria included being aged under 18 or over 55 years, having a history of neuromusculoskeletal problems or injuries resulting in scoliosis or inability to exercise safely on the FRED, being pregnant, having heart disease and having had abdominal or spinal surgery in the last three years. In addition, four participants' kinematic data and seven participants' FRED data were excluded due to technical errors with data not having been recorded for them. All participants were required to pass the Physical Activity Readiness Questionnaire prior to testing. Using the same method as earlier FRED studies (Winnard, D., et al., 2017b), all participants were divided into two groups for comparison, those with and those without back pain. This was done by asking participants "how much back pain have you had in the past 4 weeks?" (modified question 7 of the Short Form-36 (SF-36), standard, US version 2 (QualityMetric, 2000)). Participants indicated their pain score, ranging from 1 (no pain) to 6 (very severe pain). Low-back pain scores of 2 or more designated participants as having back pain for analysis. There were 78 participants who reported no back pain, and 70 who reported at least very mild back pain.

Protocol

Six hundred seconds of kinematic, exercise frequency and foot-movement variability data were simultaneously collected during FRED exercise from the moment participants began exercising on the device. Participants were first time FRED users and did not undertake a pre-exercise familiarisation period. Explanation was given of the visual feedback which the device provides to help users maintain a target frequency of 0.42 Hz that produces a slow movement consistent across all participants and FRED studies. The target frequency was designed to force users to exercise in a slow and smooth movement, that is expected to me more useful than fast or jerky movements, for promoting core stability and spinal robustness (details published in previous paper (Winnard, et al., 2017c)). The foot movement amplitude can be adjusted on the FRED and for this study was set to the smallest amplitude (0.2 m) for all participants. The smallest amplitude setting was selected as it considered to be the easiest setting for the first time users and is in line with our other studies (Winnard, et al., 2017c; Winnard, Debuse, Wilkinson, Tahmosybayat, & Caplan, 2017b).

Outcome measures

Lumbopelvic kinematics were assessed by measuring sagittal plane joint angles at L5/S1, L3/L4, T12/L1 and T8/T9 and pelvic tilt. These measures are relevant to LM and TrA training, as they provide an estimate of full lumbar lordosis, lower thoracic kyphosis and sagittal plane pelvic tilt and were the same as those measured in a previous study (2017b). Current clinical LM and TrA training aims to promote and maintain lumbar lordosis within the lumbar spine (O'Sullivan et al., 2006; Roussouly, Gollogly, Berthonnaud, & Dimnet, 2005) as LM controls the

lumbar lordosis (Claus, et al., 2009). Kinematics were assessed using a wearable-motion-capture system (MVN, XSens, Enschede). The system consists of a series of motion tracking devices placed at key locations within a wearable suit that was placed over a single layer of participant's clothing, who wore t-shirt and trousers, in line with published guidelines (Roetenberg, Luinge, & Slycke, 2013) and our previous study methods (Winnard, D., et al., 2017b). Seventeen sensors containing a 3D gyroscope, 3D accelerometer and a magnetometer, were secured to the hands, forearms, upper arms, head, scapulae, pelvis, upper legs, lower legs and feet. An image of the exact tracker locations is available elsewhere (2017b). Participants were required to remove footwear throughout the trials to prevent any confounding effect of footwear design. Full body kinematic data were collected at 80 Hz, using the default full body model and Kinematic Coupling Algorithm (KiC) fusion engine setting. Local magnetic interference can cause drift over prolonged use of this system, so the magnetometer input was disabled to minimise drift errors. For modelling the spinal segments, data is taken from the sacrum, sternum, scapulae and head trackers. The spine is divided into segments with joints estimating movements at L5S1, L3L4, L1T12 and T9T8. The movements of these joints were estimated by the software using interpolation between the trackers. This is the default setup recommended by the XSens user manual, which states these segment definitions match International Society of Biomechanics recommendations (XSens, 2012). Data from the trackers is used to displace the default spinal model. The displacement movement is divided across several segment joints based on a stiffness assigned to each segment within the software.

The Xsens system was reported as having up to two degrees of error for dynamic accuracy in roll, pitch and heading linked to centre of mass and pelvic tilt data, and an angular resolution for joint angle estimation of 0.05 degrees (Lebel, Boissy, Hamel, & Duval, 2015). The system has been validated against the gold standard VICON 3D system for measuring kinematic data (Roetenberg, et al., 2013) and shown to have good correlation with optical motion capture systems for estimated 3D kinematics at the L5S1 level (Faber, Chang, Kingma, Dennerlein, & van Dieen, 2016).

Exercise frequency and foot movement variability were assessed using a rotary encoder built into the FRED (RP6010, ifm Electronic GmbH, Essen, Germany). Frequency was calculated as the number of crank cycles per second (Hz). Movement variability was quantified as the difference (%) between the instantaneous-angular velocity of movement and the mean-angular velocity over the previous second. This was recorded as a negative change if the live velocity was decreasing and positive if it was increasing. Movement variability data were made absolute for analysis, meaning a high movement variability value indicated uneven movement while a movement variability of zero represented perfectly even movement (i.e. constant angular velocity of the feet). The frequency and movement variability data were recorded at 5 Hz on a second PC, running custom software. This sampling rate was the fastest the FRED hardware and software was able to record. The frequency and movement variability data was collected over the same time period as the Xsens data. The data were imported into Microsoft Excel 2010 for analysis.

Data analysis:

Familiarisation time was defined as the time at which participants first achieved correct technique after movement initiation. Correct FRED exercise technique requires upright posture and a relatively stable lumbopelvic region, during slow and controlled cyclical-functional movements of the lower limbs (Debuse, et al., 2013). Poor exercise technique may therefore be defined as variation beyond the amount measured during a period of familiarised exercise.

The mean and standard error of the mean (SEM), across each participant was calculated for every data point for both groups, as used in previous biomechanical familiarisation studies (Moore and Dixon, 2014). The mean ± SEM range was plotted as a function of time for flexion angle at L5/S1, L4/L3, L1/T12, T8/T9, anterior pelvic tilt, exercise frequency and movement variability. To enable clear analysis, without losing the overall pattern, several filtering options were assessed. The smallest moving average which reduced noise sufficiently to allow clear analysis to be made was selected. A moving average filter was therefore selected for each variable with a time window of 2.5 seconds before and after each data point.

All data appeared to have plateaued, indicating familiarisation, by 2.5 minutes and remained stable until at least 4.5 minutes, showing no loss of technique occurred within this period. Therefore the mean between 2.5 and 4.5 minutes was used as a familiarised reference. The familiarised reference mean ± the mean SEM of each measure between 2.5 and 4.5 minutes was plotted as a familiarisation reference range based on the likely range of the true mean. Familiarisation was estimated to be the point (to the nearest 5 second interval) at which the mean ± SEM

across all participants fully entered into the familiarisation reference range for each variable. Any variables that crossed over the familiarised region, before the 2.5 minute point and continued to fluctuate while still overlapping the familiarised range and before reaching an obvious plateau were not considered familiarised until fluctuations decreased and the plateau was reached.

Magnitude based inference (MBI) was used to determine if the mean difference before and after the familiarisation point was at least as large as the familiarised reference SEM. Magnitude based inference has recently been proved a trustworthy alternative to traditional significance testing and outperforms in sample size, error rates and publication bias (W. G. Hopkins and Batterham, 2016). For all estimated points, the mean difference, 90% confidence intervals and probabilities (%) that the true values of the statistic were mechanistically positive, trivial or negative based on the smallest worthwhile change (familiarisation reference SEM) were reported and qualitatively defined by the following scale recommended by Hopkins, et al. (2008) as <0.5% is "*most unlikely*", <5% is "*very unlikely*", <25% is "*unlikely*", 25-75% is "*possible*", >75% is "*likely*", >95% is "*very likely*", and >99.5% is "*most likely*". All inferences which were at least likely (>75%) were highlighted using bold text in the results. Full raw data sets are available from the authors on request.

Results

Table 1 presents the pain and no pain group demographics. The group demographics and any differences found with MBI are, therefore, presented taking these exclusions into account. Any differences between the groups were *trivial*.

Figure 1 illustrates the mean ± SEM for L5/S1 kinematics as an example variable, throughout the 600 second trials, compared to the familiarised reference ranges, in both the pain and no pain groups. All other familiarisation figures can be requested as supplementary data from the authors. The reference familiarisation ranges are marked with horizontal dashed lines on the plots and any estimated familiarisation points by vertical dotted lines. Table 2 presents the raw change in mean and 90% confidence limits of each measure, before and after the estimated familiarisation and loss of technique points, and MBI.

All flexion angles were familiarised by 40 seconds, in the no pain group and 45 seconds in the pain group, and flexion decreased during the familiarisation period in both groups. Table 2 shows it was *likely* that flexion angles were positive in both groups before the estimated familiarisation point, compared to afterwards.

Pelvic tilt appeared familiarised by 105 seconds in the no pain group and 110 seconds in the pain group, decreasing during the familiarisation period in the no pain group and increasing in the pain group. However, Table 2 shows that it was *unlikely* that anterior pelvic tilt was positive before the familiarisation point in the no pain group and *unlikely* negative before familiarisation in the pain group, compared to afterwards. The mean pelvic tilt data always overlapped the familiarised range and so familiarisation was estimated to be the point of plateau within the range.

Exercise frequency was familiarised by 70 seconds in the no pain group and 15 seconds in the pain group. Frequency decreased during the familiarisation period

in the no pain group and increased in the pain group. Table 2 shows it was *likely* that frequency was positive before the estimated 70 second familiarisation point in the no pain group, compared to afterwards. However, it was only *possible* that frequency was negative before the 15 second estimated familiarisation point in the pain group, compared to afterwards. The mean pelvic frequency always overlaps the familiarised range and so familiarisation was estimated to be the point of plateau within the range.

Movement variability was familiarised by 130 seconds of exercise in the no pain group and 155 seconds in the pain group. Movement variability decreased during the familiarisation period in both the no pain and pain groups. Table 2 shows that before the estimated 130 and 150 familiarisation points, in the no pain and pain groups respectively, movement variability was *most likely* positive, compared to afterwards.

Discussion

The main finding of this study was that it took up to 170 seconds to familiarise to FRED exercise in the no pain group and up to 150 seconds in the pain group. Spinal positioning was the first element to familiarise in both groups. Spinal positioning started in a more flexed position and gradually extended at all measured angles during familiarisation. This agrees with a previous study of 130 participants that showed FRED promotes extension in the lower portion of the spine compared to walking (Winnard, D., et al., 2017b). Exercise frequency increased in the no pain group and decreased in the pain group, while movement variability gradually decreased in both groups, throughout familiarisation. No *likely* mechanistic change

in pelvic tilt orientation occurred throughout the 600 second trials. Previous research (Gibbon, et al., 2013) and the reference data both showed that FRED exercise places the pelvis into increased anterior tilt compared to walking, and so it appears from this study that the shift in pelvic tilt occurs immediately on initiating exercise.

It is known that the LM and TrA muscles are active in a more tonic pattern during FRED exercise than walking(Caplan, et al., 2014), and more active than at rest(Debuse, et al., 2013). It is also known that LM has a role in spinal positioning, with increasing activity when the lumbar spine extends into a lordotic curve below the thoracolumbar junction (Claus, et al., 2009; O'Sullivan, et al., 2006; Roussouly, et al., 2005). As spinal posture is the first element to familiarise it is reasonable to imply that the LM muscle is likely to be active by 40 seconds of exercise in those without, and by 45 seconds in those with, back pain. The remaining familiarisation time then appears to be taken up by attempting to reach an even paced global movement pattern at the target frequency. In the no pain group, movement variability familiarised by 130 seconds followed by exercise frequency at 170 seconds. This suggests that device users focus first on achieving an even movement followed by reaching the correct frequency. However, those with back pain had no *likely* frequency familiarisation time suggesting they were able to reach the target frequency from initiating movement. The target frequency provided by the feedback was 0.42 Hz as per the rationale explained in Winnard et al.(2017c) and it is felt that users are familiarised once they are able to exercise close to this frequency with low movement variability. The familiarised frequency ranges were found to be 0.48±0.01 Hz for the no-LBP group and 0.50±0.01 Hz for the LBP group. The no-LBP group were, therefore, able to exercise closer to the target frequency, whereas

the LBP group had a frequency that was 0.12 Hz faster. This finding might suggest that those with no back LBP had better motor control. If so, this could be an indication of the FRED being a potentially useful intervention to improve motor control but this needs testing in clinical trials.

Additionally, despite the much quicker frequency familiarisation time which led to a faster overall familiarisation time, the LBP group took 20 seconds longer to develop familiarised movement variability. As people with LBP often have reduced motor control of deep lumbopelvic muscles such as LM (J. A. Hides, Stokes, Jull, & Cooper, 1994; Hodges and Moseley, 2003; Panjabi, 2006) it is unsurprising that they took more time to develop the motor control required to refine the movement, and showed reduced ability to reach the target exercise frequency. This finding therefore adds to the justification of a clinical trial of the FRED as an intervention for challenging and training lumbopelvic motor control in LBP patients to test this possibility.

Only six participants indicated experiencing severe or very severe pain. Therefore, the back pain results are mostly representative of populations with very mild to moderate back pain and should be treated with caution in populations with severe or worse pain. The back pain group does not necessarily represent a group that would all benefit from spinal motor control rehabilitation.

For first time users of the FRED, it took 170 seconds to familiarise to the exercise in terms of pelvic and spinal kinematics, exercise frequency and movement variability, while overall familiarisation occurred 20 seconds earlier in participants

with back pain as they moved at the slow target frequency from the start of exercise. Those with back pain took 20 seconds longer to achieve a consistent movement pattern, probably due to reduced motor control, and demonstrated less ability to modulate exercise frequency, suggesting the intervention might be useful as a motor control intervention. Therefore, it is recommended that future FRED activites include a familiarisation period of at least 170 seconds to allow correct lumbopelvic positioning and control of the movement to be reached.

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Figure captions

Figure 1. Mean L5/S1 flexion angle across all participants throughout the 600 second trial in; a. the no pain group and b. the pain group. Familiarisation range shown on plots between dashed lines is no pain group: 2.7±0.3, pain group: 3.4±0.3 (degrees).

Figure

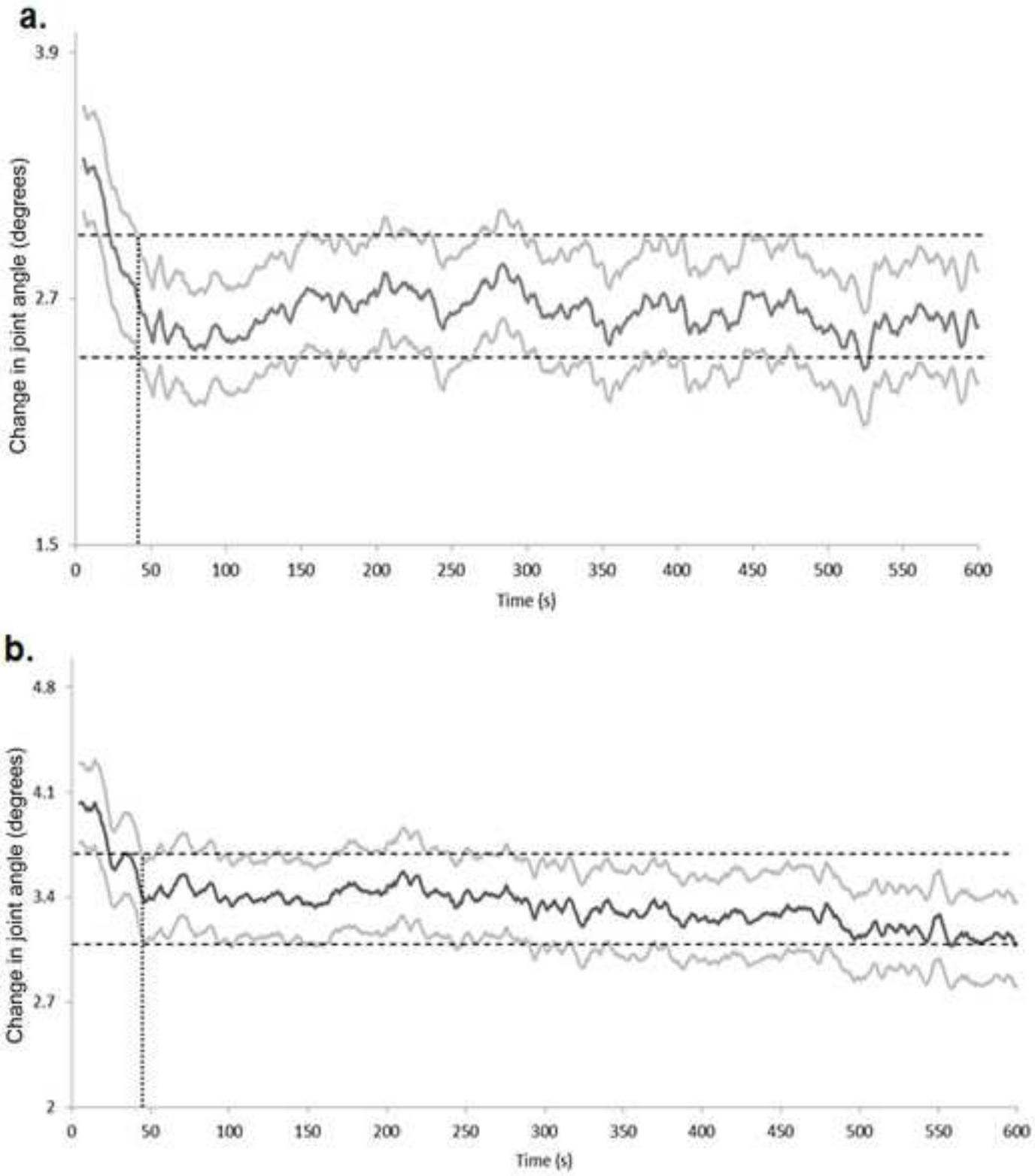
a.
3.9
2.7
1.5
Change in joint angle (degrees)
0
50
100
150
200
250
300
350
400
450
500
550
600
Time (s)
b.
4.8
4.1
3.4
2.7
2
Change in joint angle (degrees)
0
50
100
150
200
250
300
350
400
450
500
550
600
Time (s)

Table 1. Group demographics and chance that any group differences are trivial using an inference threshold of 0.6 standardised mean change.

	n	Gender (M/F)	Age (years)	Mass (kg)	Height (m)	BMI
Kinematic data						
All participants	144	73/71	36.5	77.8	1.72	26.3
Back pain	67	33/34	37.6	80.3	1.72	27.1
No pain	77	40/37	35.7	75.6	1.72	25.6
Chance (%) that difference between pain and no pain groups is trivial			100	97	100	100
FRED data						
All participants	141	71/70	36.8	78.4	1.72	26.3
Back pain	67	33/34	37.6	81.1	1.72	27.2
No pain	74	38/36	36.1	75.9	1.72	25.6
Chance (%) that difference between pain and no pain groups is trivial			100	94	100	98

Table 2. Differences in L5/S1. L3/L4, T12/S1 and T8/T9 flexion angles, pelvic tilt, exercise frequency and movement variability pre and post familiarisation point.

Group	Comparison time point	Raw change	90% confidence limits		Mechanistic inference
L5/S1 flexion angle. Inference threshold: 0.3 degrees no pain and pain group					
No pain	40 s	0.4	0.6	0.2	Likely +ve
Pain	45 s	0.4	0.6	0.2	Likely +ve
L3/L4 flexion angle. Inference threshold: 0.1 degrees no pain and pain group					
No pain	40 s	0.2	0.3	0.1	Likely +ve
Pain	45 s	0.2	0.3	0.1	Likely +ve
T12/L1 flexion angle. Inference threshold: 0.1 degrees no pain and pain group					
No pain	40 s	0.2	0.3	0.1	Likely +ve
Pain	45 s	0.2	0.3	0.1	Likely +ve
T8/T9 flexion angle. Inference threshold: 0.1 degrees no pain and pain group					
No pain	40 s	0.1	0.2	0.0	Likely +ve
Pain	45 s	0.2	0.2	0.1	Likely +ve
Anterior pelvic tilt. Inference threshold: 0.1 degrees no pain and pain group					
No pain	105 s	0.4	0.4	0.0	Unlikely +ve
Pain	110 s	-0.4	0.1	-0.9	Unlikely -ve
Exercise frequency. Inference threshold: 0.014 Hz no pain and pain group					
No pain	170 s	-2.4	-1.5	-3.3	Very likely -ve
Pain	15 s	1.7	4.0	-0.7	Possibly +ve
Movement variability. Inference threshold: 1.5% no pain and 1.6% pain group					
No pain	130 s	4.2	4.8	3.6	Most likely +ve
Pain	155 s	3.2	3.6	2.7	Most likely +ve

Threshold for inferences using mean SEM between 2.5 and 4.5 minutes is indicated in table. All raw change and confidence limits are in degrees.